Marine Policy 88 (2018) 323–332

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Ecotourism, climate change and reef fish consumption in Palau: Benefits, trade-offs and adaptation strategies

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ARTICLE INFO

Keywords:
Sustainable fisheries
Diving
Subsistence
Marine protected area
Bio-economic
Climate change adaptation
Small-scale fisheries
Integrated management

ABSTRACT

Marine ecosystems play a central role in economic and social life in the Republic of Palau, a Small Island Developing State in the Western Pacific. Marine resources underpin subsistence and commercial fisheries, as well as tourism activities, contributing substantially to Palau's GDP and employment. Since 1992, Palau has been actively developing conservation initiatives to protect marine resources, promote ecotourism, and ensure revenue generation. Marine reserves represent a particularly important tool in the country's sustainable development strategy. In 2015, Palau designated 80% of its marine EEZ as a National Marine Sanctuary, with the remaining 20% slated for domestic fisheries. That same year, Palau received 160 thousand tourists, over 9 times the country's population. In early 2017, the President proposed a bill effectively limiting budget travel and actively promoting high-end tourism. This study uses a quantitative social-ecological model to explore policy scenarios involving tourism, marine conservation and local food security. While climate change had the largest expected impact on local ecosystems, reef fish consumption contributes considerably to future projected declines in marine resources. Therefore, for Palau to achieve its goals of boosting revenues while sustainably stewarding marine resources, it will be necessary to transfer some level of consumption from reef fish on to tuna and other pelagics. Such changes, which align with the current proposal of developing an offshore national fishery as part of the Sanctuary's management plan, may allow Palau to meet future seafood demand, while protecting reef systems and the industries that rely on them.

1. Introduction

The Republic of Palau is an archipelago consisting of over 700 islands (only 12 of which are inhabited) stretching over 700 km in southwest Micronesia, about 750 km east of the Philippines and 1300 km southwest of Guam. A barrier and fringing reef complex encircles most of the archipelago, creating a vast lagoon of varying depth with an area of over 1200 km^2.

Palauans have a long history of a strong relationship with the ocean as central to their culture and social organisation [1,2], and a source of food and livelihoods [3–5]. A 2003 survey indicates that 87% of households are linked to fishing for subsistence or commercial purposes [6]. The adoption of new fishing technologies and strategies over time has led to a greater understanding of fish behaviour and exposure to a greater variety of environments [7]. However, such developments have also resulted in increased fishing pressure in coastal environments [8], especially close to urban centres, with a number of studies indicating important declines in the biomass and abundance of reef fish populations [6,9–11]. A recent study shows that most fishers in the more rural northern province perceive that catches today are about half what they were seven years ago, that reef fish in general are much smaller now, and that local reefs are severely overexploited as a result of the current level of local-, tourism- and export-driven demand for fresh fish [12].

Marine protected areas (MPAs) have been a central element to Palau's goal to protect marine biodiversity and allow for the sustainable exploitation of marine resources. In 1996, a national conservation law was enacted for the preservation of both terrestrial and marine wildlife. In 2003, Palau legally established the Protected Area Network (PAN) to effectively conserve local natural resources, and in 2009 Palau declared the world's first shark sanctuary. The country was also instrumental in establishing the Micronesia Challenge, an initiative between the Federated States of Micronesia, the Republic of the Marshall Islands, the Republic of Palau, Guam, and the Commonwealth of the Northern Mariana Islands to protect more than 30% of the region's nearshore

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http://dx.doi.org/10.1016/j.marpol.2017.07.022
Received 31 March 2017; Received in revised form 25 July 2017; Accepted 31 July 2017
Available online 19 September 2017
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marine ecosystems by 2020. Today, 23 MPAs and the Southern Lagoon Management area account for over 45% of Palau's coastal habitats being under some form of protection and/or management (albeit only 14% of Palau's reefs and seagrass beds are effectively in no-take zones [11]). In October 2015, Palau committed to the creation of a new National Marine Sanctuary [13,14]. The Sanctuary's objectives include a ban on all foreign fishing for tuna and other large pelagic fish, support for the development of an offshore national fishery in 20% of the Exclusive Economic Zone (plus territorial sea out to 12 nm), and closure of the other 80% to any type of extraction by 2020 (Fig. 1). The national pelagic fishery would land all catches in Palau to supply fresh fish to local markets, increase food security and, by reducing fishing pressure on reef fish, support tourism.

Palau's rich marine environment and the protection the country has afforded its biodiversity play an important role in generating income. Tourism, particularly ecotourism, contributes to about three quarters of GDP growth, 15% of total tax revenue, and 40% of total employment [15]. The value to Palau's economy of protecting sharks, one of the main attractions for tourists visiting Palau, was estimated at US$1.9 million through dive tourism, compared to US$10,800 if these sharks were killed for sale [16,17]. There are many definitions of 'ecotourism' [18], and it is used here to refer to activities focused on watching marine living organisms or natural areas, with an expectation of concurrent benefits to local ecosystems and human communities (sensu [19]). This contrasts with 'nature-based tourism' where conservation or local benefits are not specifically promoted. This distinction is relevant as this study departs from the assumption that sustained benefits to local social-ecological systems will necessarily follow from nature-based (or "ecotour-ish" [20]) activities, though they certainly could [21]. While tourism packages to Palau may not necessarily have the promotion of local benefits in mind, green fees collected from all tourists at departure, and for diving, snorkelling or any other water-based activities, specifically support conservation initiatives. Indeed, revenue from these fees is used for a number of actions, including the development of Palau's PAN and better sewage management.

While tourism development significantly contributes to local incomes and provides a key source of employment in many coastal communities [22,23], it also presents a number of challenges (e.g., [24,25]). The promotion of Palau as an outstanding dive destination has been successful, with visitor arrivals more than doubling over the last decade to 160,370 in 2015, representing about 9 times the local population [26,27] (Fig. 2). However, such large numbers of, often inexperienced, divers have raised concerns about overcrowding at dive sites and poor diver behaviour (e.g., coral holding or kicking, full body layouts on corals, etc.) contributing to coral reef decline [28-31]. Visitation rates have also led to increased pressure on resources through greater freshwater usage, mostly reef-sourced seafood consumption in restaurants, rapid coastal development to accommodate and provide for a greater influx of people, and increased waste generation [6,11].

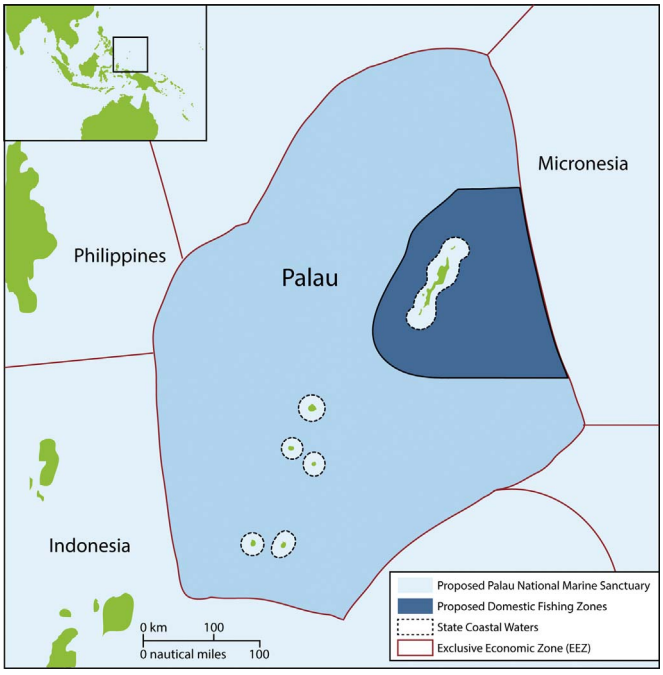

Fig. 1. The Palau National Marine Sanctuary (500,000 km^2, 80% of Palau's Exclusive Economic Zone), in which no extractive activities will be permitted by 2020, and the proposed domestic fishing zone.

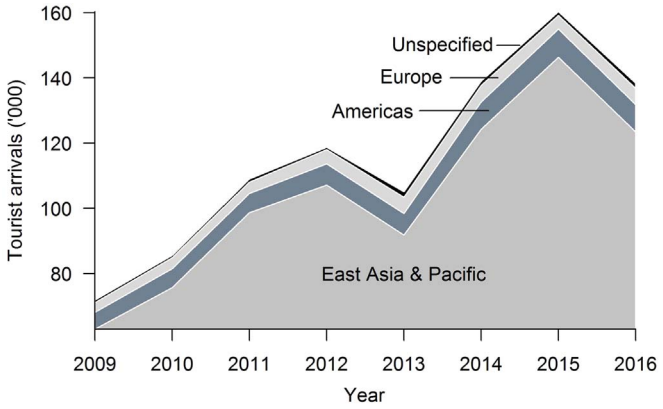

Fig. 2. Tourist arrivals (in thousands) into Palau, according to region, between 2009 and 2016, [27].

In light of negative tourism impacts, President Remengesau recently proposed a bill that would deter budget travel and only allow high-end, high-value resorts and hotels on the island, with corresponding recreational activities for luxury tourists [32,33]. By halving flights from China, transporting mainly package tour travellers, visitor rates declined by 15% in 2016 [27] (Fig. 2). The new strategy outlined by the President also seeks to use tax breaks and other benefits to attract investors who would be willing to improve upon existing, and develop new, sanitation and water treatment systems.

Given Palauan's strong ties to the oceans, a significant underlying challenge is posed by climate change, expected to impact not only marine environments, but also Palauan's culture and livelihoods. Reefs throughout the archipelago experienced considerable bleaching and as high as 90% mortality during the 1997–1998 El Niño event, with further mortality recorded during the 2001 and 2010 thermal stress episodes [34–37], and the 2012 and 2013 Bopha and Haiyan super typhoons [38]. While species richness recovered 10 years after the first El Niño, reef composition has changed [34,39]. Reefs located in bays suffered lower bleaching rates than those on outer and patch reefs [34], and while they may therefore shelter some species from climate change, these reefs are more vulnerable to land-use modifications and other human impacts [34,37,40].

This study outlines a quantitative social-ecological framework to explore the current and future impacts of tourists on reefs through diving activities as well as fish consumption, and ascertain consequences for local lifestyles against the backdrop of climate change. Potential trade-offs are outlined through specific scenarios, including: (i) climate-related impacts on marine ecosystems; (ii) direct diver impacts; (iii) reef fish consumption by both locals and tourists; and (iii) currently proposed government tourism and conservation strategies. Results are discussed in the context of policy development to inform future sustainable marine resource management in Palau.

2. Materials and methods

2.1. Study area

While this study discusses trade-offs for Palau as a nation, marine tourist activities chiefly take place around the “Rock Islands”, located just to the south of the main island (Fig. 3) and consisting of tectonically uplifted coralline limestone. This area, also referred to as the “southern lagoon”, covers an area of approximately 500 km^2, and includes extensive barrier reefs, as well as the greatest number of patch reefs and islands [8]. Coral reefs in Palau cover between 525 and 892 km^2 [41,42], hosting the most diverse coral fauna of Micronesia and the highest density of tropical marine environments of any area in the world of comparable size [1].

All of Palau's most popular dive sites are located on the southern portion of the southern lagoon and barrier reef (Fig. 3). Thus, the tourism value of Palau's reefs depends on relatively small areas attracting the vast majority of tourism activity.

2.2. Model framework

Four social sectors were considered in the model system (Fig. 4): resident Palauans; tourists, consisting of general tourists and ecotourists (divers and snorkellers); and locally-based as well as foreign-based offshore fisheries. Currently, tuna fishing in Palau's Exclusive Economic Zone is the second highest income generating mechanism for the country after tourism. Offshore fisheries are dominated by the locally-based foreign longline fleet of Chinese Taipei and the offshore-based longline and purse seine fleets of Japan [44]. Given the coastal focus of this study, and that offshore waters will effectively be protected from fishing under the Protected National Marine Sanctuary Act by 2020 (after a five-year phase-in period), the latter sector was noted conceptually and in the discussion, but not integrated into the quantitative model presented here.

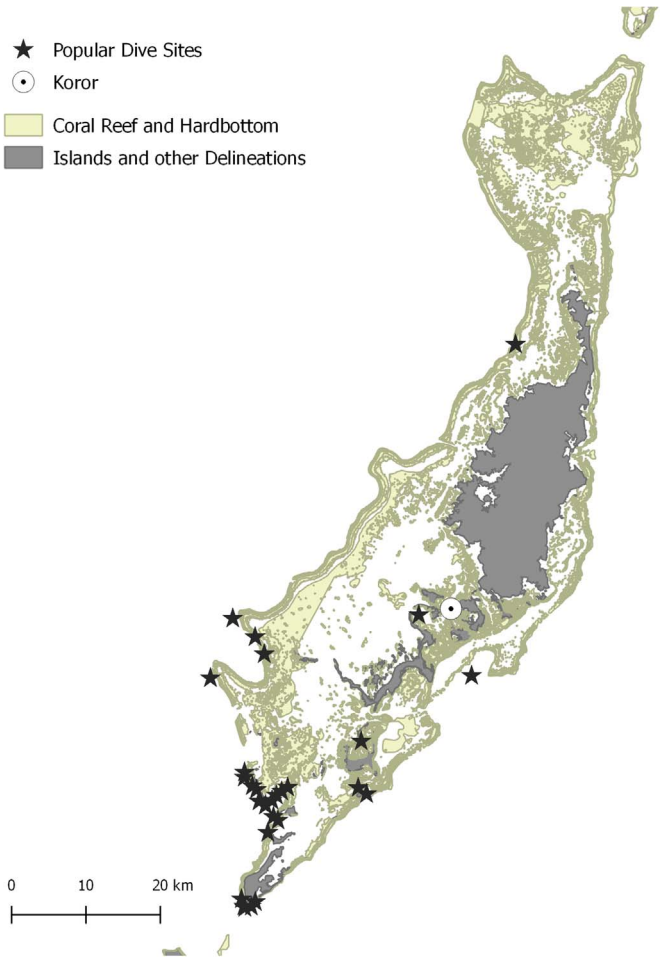

Fig. 3. Main islands of the Republic of Palau (dark grey), with coral reef and hardbottom habitats as defined by Battista et al. [43], most popular dive sites (stars) and Palau's main commercial centre, Koror.

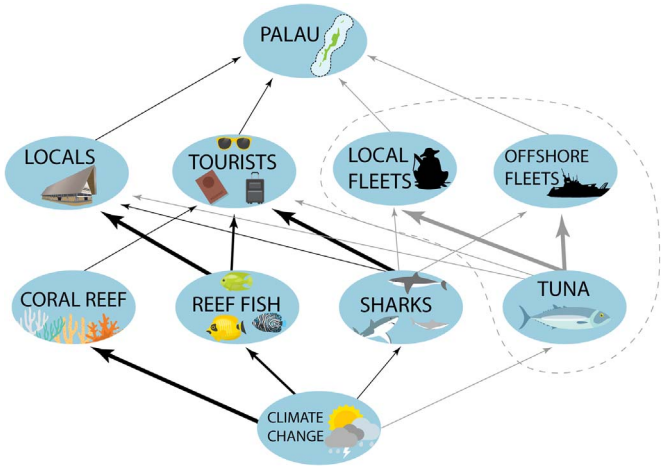

Fig. 4. Conceptual model framework, including physical (climate change), ecological (coral reef, reef fish, sharks), and human (local population, tourists, fishing fleets) sectors. Components encircled by a grey dotted line (tuna stocks, local fishing fleets, local- and foreign-based offshore fleets) are considered conceptually, but not included in the quantitative model. The thickness of the arrows illustrates the importance of individual impacts or contributions of one component (on) to another.

2.2.1. Ecotourists

‘Ecotourists’ represent divers and snorkellers, who are reported to make-up between 50% [16] and 94% (derived as the ratio of Rock Island lagoon permits to total number of tourists [30]) of total visitors. A comprehensive exit survey conducted by the Palau Visitors Authority in 2001 [45], showed that nearly 70% of visitors to Palau are divers. However, the recent surge in arrivals from China has been linked to an increase in boat tour spending and a decline in tourist diving expenditures [46]. The latter may be a reflection of tourists making fewer dive/snorkel trips while on island, and/or spending less on such activities. Our model was conservatively parameterised with an initial ecotourist to total tourist ratio of 0.5, and total tourist arrivals set at 160,000, rounded down, for simplicity, from the 160,370 arrivals recorded in 2015 ([47]– see Fig. 2).

2.2.2. Locals

‘Locals’ are resident Palauans, many of whom engage in fishing activities and who predominantly target and eat reef fish. Subsistence fishing remains an important activity in Palau, with currently few commercial fishers – though no statistics exist to specify exactly how many – depending exclusively on their catches for income [10]. The important growth of tourism has fostered a cash market for fresh fish, with fishing therefore becoming an increasingly reliable and important commercial activity. Hotels and restaurants are the main buyers of fresh fish, and often purchase directly from select fishers. JR5 market (formerly known as Happy Fish Market), located in the main urban centre of Koror, is the only fresh fish public market where the majority of catch is landed for sale to the public and restaurants [10,48]. Until recently, most commercial coastal fisheries operated around Koror. However, with declining local fish abundance, Gleason et al. [12] estimate that 30–50% of reef fish being landed at JR5 are now being taken from the Northern Reefs by Koror-based fishers.

2.2.3. Reef fish

'Reef fish' are represented here as a single group and comprise the main species belonging to the families Acanthuridae, Lutjanidae, Lethrinidae, Scaridae, Siganidae and Serranidae, known to be targeted by local fishermen [10,49,50] and representing ~90% of total reef fish catches [51]. Population dynamics of reef fish were modeled as denoted in Eq. (1), where biomass (B), at time t is:

$$B_t = B_{t-1} + r \bullet B_{t-1} \bullet (1 - B_{t-1}/K_{t-1}) - \sum_j Q_{j,t} \quad (1)$$

Here, K is the climate-driven fish carrying capacity (see section 2.2.5), r is the maximum intrinsic rate of population increase, and Q is the human consumption of fish per sector j (i.e., tourists and locals) (see next section below). Carrying capacity was estimated based on Martell & Froese [52], available data for total (subsistence and commercial) local reef catches for 2009 [53], and assuming that, at the time of data collection, these catches represented maximum sustainable yield. As few reliable estimates of r were available for most of the main landed species [10,49,50], r was derived from Fishbase (www.fishbase.org) for species within the same families and classified according to the same resilience category for which data were accessible. The model value was then estimated as the weighted average according to individual fish families' contribution to total catches [51].

2.2.4. Annual reef fish consumption

Estimates of annual average consumption of fresh fish by locals range from 33 kg (though this is almost certainly an underestimate; [54]) to 78 kg [51], 85 kg [55] and 135 kg [56]. Based on more recent available information, Gillett [53] provides a local fish consumption rate of 123 kg. Based on these data and expert feedback, the assumption was made that locals consume an average 98 kg of fish per year, 70% of which is self-caught (i.e. not purchased at a cash market) [57], and that 90% of their fish intake, on average, consists of reef fish. Intake by tourists was calculated as the average fresh fish consumption per capita in tourists' countries of origin, weighted by the proportion of arrivals from each region into Palau in 2015, scaled by the average number of days spent in Palau [16] and the average proportion of meals consisting of reef fish consumed by tourists while on island (80%; Ian Bertram, pers. comm. based on a rapid assessment survey of the main local restaurants). Total consumption of reef fish is then calculated using these per capita rates and the total number of people in each sector (N) according to:

$$Q_{j,t} = N_{j,t} \bullet q_j. \quad (2)$$

2.2.5. Climate change impacts

Sharks and coral are represented through an index of relative abundance (K) that declines over time given expected impacts of climate change. This parameter is also used in the estimation of yearly reef fish carrying capacity (Eq. (1)). Climate change impacts on reef fish, sharks, and coral are thus incorporated through the carrying capacity parameter or index of relative abundance (K), respectively, and a specific climate change impact coefficient (τ) for each group (i) (Eq. (3)).

$$K_{i,t} = K_{i,1} \bullet (1 + \tau_{i,t}) \quad (3)$$

Higher temperatures have been projected to lead to declines in fish biomass [58,59]. While the level of impacts can be variable, in the absence of location-specific data, values were used here as reported in the literature for reef fish (−45%), shark abundance (−12%), and coral reef state (−75%) [60–62] in the South Pacific region, under a 100-year time horizon [63]. These values were applied as a gradually increasing yearly impact over the twenty years used here for simulations. This time frame was chosen as it is relevant for economic projections and fisheries management actions.

2.2.6. Diver impacts and index of ecological state

For coral, the model includes impacts of divers through direct contact, abrasion and breakage. Poonian et al. [29] estimated diver contact rates with hard coral in Palau, prior to the surge in tourist arrivals and less experienced divers [64] (first author pers. obs. in 2015), at between 3.5 and 11.9 per diver per 40 min-dive (average of 0.19 min^{-1}). This is lower than a review of published data from other localities with high visitation rates (e.g., [65–71]) yielding an average contact rate of 0.3 min^{-1}. Contact rates can result in breakage and mortality [72], reducing reproductive output [73]. Even in instances where corals are not broken, human contact with the reef can result in reduced reef health due to tissue abrasion [65], which can significantly increase disease prevalence [74,75] and lower growth rates [69]. Damage rate per diver (D) was estimated here based on Saphier and Hoffmann [76] with: an average length of stay and number of dives derived from Vianna et al. [16,17]; dive contact rate taken from Poonian et al. [29]; a 40 min dive duration based on the first author's personal observation; average damage rate estimated from publications reporting from sites with high visitation rates [65,68,77–79]; coral area derived from Battista et al. [43]; and coral cover estimates taken from Golbuu et al. [6,39]. Thus, the relative state of coral reefs (*Coral*) over time was calculated as:

$$Coral_{t+1} = K_{c,t} \bullet (Coral_t - N_{ecotourists,t} \bullet D) \quad (4)$$

Surveys conducted by Koike et al. [80] indicate that coral reef deterioration would result in a 10% decline in visitors, in line with findings by Graham et al. [81] following the 1998 mass-bleaching event in Palau, and other studies around the world (e.g., [82–85]). Sharks and large pelagics, as well as sizeable reef-associated fish such as Napoleon wrasse (*Cheilinus undulatus;* locally known as maml) and bumphead parrotfish (*Bolbometopon muricatum;* kemedukl), are key tourist attractions [17,80]. It was therefore assumed that their presence contributes disproportionately more to tourists' decision to engage in diving activities in Palau (termed here as "attraction weight") than corals themselves [86]. Based on available survey data [80], attraction weights (A) for sharks, reef fish and coral were set at 0.5, 0.4, and 0.1, respectively. These parameters are then used, together with relative abundance/state I of sharks, fish and coral, to estimate a yearly index of ecological state (*EI*) with respect to diver preferences:

$$EI_t = \left[\sum_i (I_{i,t} \cdot A_i) / \sum_i A \right] / EI_{t=1} \quad (5)$$

2.2.7. Number of ecotourists

The number of yearly ecotourists (*ET*) is estimated assuming that inferior ecosystem state (*EI*) results in a decline in the number of divers and snorkellers according to:

$$ET_t = \alpha \bullet e^{EI_t \bullet \beta} \quad (6)$$

In the baseline scenarios, the scale (α) and slope (β) parameters in Eq. (6) assume that an ecosystem state of 1 (current conditions) results in 80,000 visiting ecotourists (i.e., 50% of total tourist arrivals). This assumption is relaxed in other model scenarios [17]. In the case of Palau, it was also assumed that ecotourism is a driver of total tourist arrivals, so that arrivals of non-diving tourists are not expected to completely replace lower numbers of ecotourists following declines in ecosystem quality.

2.2.8. Market benefits to the Palauan economy

Total market benefits to the Palauan economy (*TR*) (Eq. (7)) were computed as the sum of fisheries revenue (*FR*) (Eq. (8)) and tourism expenditures (*TE*) (Eq. (9)). Fisheries revenue (*FR*) was estimated based on catch destined to both local and tourist markets, with a specific ex-vessel price (p) for each sector: US$3.75/kg [53] and US$12.5/kg (first author pers. obs. and multiple pers. comm.), respectively. Tourist numbers surged in 2015, with most arrivals originating from China

(> 50%; Fig. 2) [28,47]. This contrasts with Palau's tourism profile between 2009 and 2014, when Japanese tourists accounted for most arrivals. The change in profile of tourist arrivals has been linked to altered expenditure patterns, with Chinese tourists spending less on accommodation [46]. These recent changes notwithstanding, to work from a baseline reflecting the more general pattern in tourism for Palau, and to be largely in line with the President's proposed strategy, the model was initialised with expenditure per capita (px) estimates for each tourist type (GT = general tourist and ET = ecotourist respectively) based on Vianna et al. [17], adjusted for inflation.

$$TR_t = FR_t + TE_t \quad (7)$$

$$FR_t = \sum_{i,j} (Q_{i,j,t} \bullet p_{i,j}) \quad (8)$$

$$TE_t = (GT_t \bullet px_{GT}) + (ET_t \bullet px_{ET}) + (TT_t \bullet GF) + (ET_t \bullet RIF) \quad (9)$$

In Eq. (9), all tourists (TT) were assumed to pay the Palau Green Fee (GF; US$50) and all ecotourists the additional Rock Island/Jellyfish Lake Fee (RIF; US$100). Expenditure on seafood (FR) was deducted from the tourism sector's expenditure estimate (TE) to avoid double-counting. Note that, due to the bottom-up estimation of fishing and tourism revenues using available data from literature and surveys, baseline revenue values may differ from government data collected using different methodologies. All scenario results are therefore intended to highlight projected trends relative to each other. Future efforts could certainly be directed at improving estimates drawing on more detailed and less readily available government and other relevant economic data sources and methods to be more in line with official statistics.

All key leading parameter values are summarised in Table 1.

2.2.9. Sensitivity analyses

To address uncertainty associated with parameter values, stochastic variation was included around estimates related to expected climate change impacts on all ecosystem components, and fish consumption by both tourists and locals (Fig. 5). Uncertainty ranges were based on available competing parameter estimates from the literature (see Section 2). All quantitative estimates listed in the Results section thus represent mean values from Monte Carlo simulations (1000 iterations) after 20 model years.

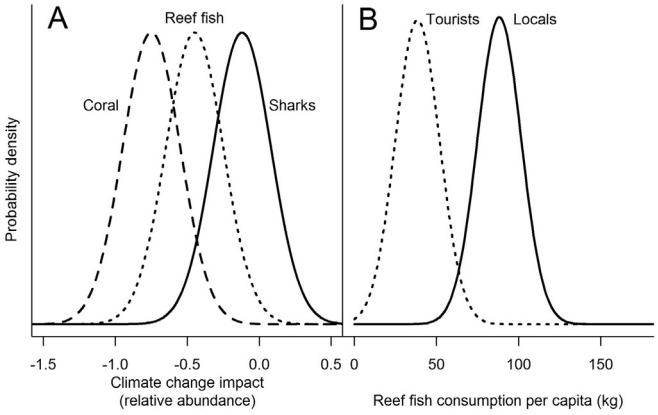

Fig. 5. Uncertainty ranges for climate change impacts on abundance/state relative to current status for sharks ($\bar{x}$ = −0.12), coral ($\bar{x}$ = −0.75), and reef fish ($\bar{x}$ = −0.45) [60–62]; and per capita consumption of reef fish by resident Palauans ($\bar{x}$ = 98 kg/yr) [51,53-56] and tourists ($\bar{x}$ = 48 kg/yr) [87].

2.2.10. Scenarios

Five management scenarios, described below, were evaluated. In each case, all parameters were held at baseline reported values (Table 1), unless otherwise specified:

1. *Baseline*: Current situation to which climate change projections on coral, reef fish and sharks were added;
2. *Poor practices*: Poor management of local habitats (e.g., poor diver behaviour, poor land use practices) increases impacts on local reef ecosystems;
3. *Limited ecotourism impacts*: Diver impacts on coral reefs (i.e., through direct contact) are reduced through effective campaigns aimed at dive operators and tourists to adopt diving/snorkelling best practices;
4. *Limited reef fish consumption*: Reef fish consumption is reduced for both tourists and resident Palauans, in line with proposals to land tuna caught in Palau locally and actively promote its consumption;
5. *Best practices*: Both direct diver impacts and reef fish consumption are effectively reduced, as per (3) and (4) above;
6. *Proposed tourism strategy*: In accordance with the President's tourism strategy, total tourist numbers decline, but the proportion of higher-

Table 1
Baseline model parameters, description, values, and references. In the 'Value' column: S = Sharks; RF = Reef Fish; CR = Coral; L = Local population; GT = General Tourism; ET = Ecotourism (snorkelling/diving). Values shown are initial model conditions, but are varied stochastically as noted in the methods.

Symbol	Description	Units	Value	Sources
r	Intrinsic population growth	–	RF: 0.475	Fishbase – see text for how overall value was derived and relevant references
K	Initial biomass for reef fish Index of relative abundance for sharks and coral	Tonnes	RF: 17,810	Gillett [53] for estimates of current catches
t	Time step	Year	–	
τ	Mean effect of climate change on group abundance (reef fish, sharks) or state (reef)	Ratio	S: −0.12; RF: −0.45; CR: −0.75	Lehodey et al. [60]; Pratchett et al. [61]; Hoegh-Guldberg et al. [62]
L	Local population	Number	17,665	Bureau of Budget and Planning [47]
TT	Total tourist arrivals	Number	160,000	Rounded down from 160,370 [47]
ET	Number of ecotourists (i.e., divers and snorkellers)	Number	80,000	Assumption that ecotourists account for 50% of total number of tourists taken from Vianna et al. [17]. Also see text.
A	Contribution of species group to ecotourism attractiveness (i.e., "attraction weight")	Percentage	S: 50%; RF: 40%; CR: 10%	Koike et al. [80]
p	Ex-vessel price for fisheries catch	$US/kg	L: 3.75; GT, ET: 12.5	Gillett [53]; First author pers. obs. verified by multiple pers. comm.
$\mathbf{Px_{GT}}$	Per-capita expenditure by general tourists	$US/capita	1610	Vianna et al. [17]
$\mathbf{px_{ET}}$	Per-capita expenditure by ecotourists	$US/capita	2185	Vianna et al. [17]
D	Per-diver impact on coral	Ratio	ET: 1×10^{-7}	Informed by: Barker and Roberts [65]; Krieger and Chadwick [68]; Roche et al. [77]; Worachananant et al. [78]; Walters and Samways [79].
q	Consumption of fish per capita	kg/yr	L: 98 GT, ET: 48	Informed by: Friedman et al. [51]; Gillett [53]; Bell et al. [54]; Preston [55]; Palau Conservation Society [56]; FAO [87]

Table 2
Scenario results for selected parameters after twenty-year simulation. Parameters other than those specified in the description are the same as "*Baseline*". Revenue from fish purchased by tourists is not included in tourism revenue. Tourist arrivals and revenue are per year. All values in 2016 $US. GT = General tourists; ET = Ecotourists.

No.	Scenario	Description	Tourists (thousands)		Ecosystem state (relative to initial)			Revenue ($US millions)			
			GT	ET	Sharks	Reef fish	Coral	GT	ET	Fishing	Total
1	*Baseline*	All parameter values as in Table 1	21.3	21.3	0.98	0.66	0.19	34.1	46.4	2.1	87.1
2	*Poor practices*	Poor management, including of diver behaviour, increases ecological impacts by 75%	16.4	16.4	0.98	0.60	0.05	26.7	36.3	2.1	68.5
3	*Less ecotourism impacts*	Diver impacts on reefs reduced by 75%	21.1	21.1	0.98	0.66	0.20	33.5	45.5	2.2	86.2
4	*Reduced reef fish consumption*	Tourist and local Palauans' consumption of reef fish reduced by 75% and 30%, respectively	31.3	31.3	0.98	0.76	0.18	50.3	68.3	1.3	126.3
5	*Best practices*	Diver impacts and reef fish consumption reduced as stated in two scenarios above	31.6	31.6	0.98	0.77	0.20	50.9	69.1	1.3	127.8
6	*Government proposed strategy*	Total tourist arrivals reduced by 30%; proportion of ecotourists increases to 70% of total; ecotourist per-capita spending increased by 20%; Green Fee for all tourists increased to $100.	8.6	21.5	0.98	0.66	0.19	13.8	56.3	2.1	77.3
7	*Proposed strategy + best practices*	As above, with reduced impacts as in *Best practices* scenario	12.6	31.5	0.98	0.76	0.20	20.2	82.6	1.3	111.9

paying ecotourists and their local per capita expenditure increases. Green fees, payable by all tourists, are also raised;

7. *Palau proposed strategy and best practices*: In addition to current government bills for tourism, direct diver impacts on coral and overall reef fish consumption are reduced (i.e., combination of (6) and (5) above).

3. Results

Findings show that overall, best practices for tourism and fisheries management in Palau include both current government proposals and a concurrent decrease in reef fish consumption, by both tourists and locals (potentially replaced by tuna and other pelagic fish), to conserve marine resources under climate change. If tourism trends continue as in 2015 (*Baseline* scenario), tourist arrivals are expected to decline significantly in 20 years' time (Table 2). This trend is due to projected declines in reef fish abundance (−34%) and coral reef state (−81%) as a result of climate change, fish consumption, and (poor) diving impacts on reefs that influence the "attractiveness" of Palau as a destination. Unsurprisingly, negative outcomes would be worsened under more lax environmental guidelines, and would result in a loss of revenue of ~US$19 million compared to *Baseline (Poor practices*, Table 2).

Over a 20-year timeline, findings suggest that climate change will significantly impact reef systems in the Republic of Palau, and focusing solely on reducing diver impacts does not emerge as a meaningful management strategy (*Less ecotourism impacts*, Table 2). Rather, a meaningful tourism management policy requires reductions in fish consumption by both resident Palauans and visitors (*Reduced reef fish consumption*, Table 2), which could dramatically increase tourist arrivals and expenditures (Table 2) compared to the *Baseline,* because of the greater attraction factor accorded by tourists to reef fish over coral [80]. Combining efforts to reduce diver impacts on reefs together with overall fish consumption (*Best practices*) yields increases in revenues of US$1.5 million compared to the aforementioned scenario. Results for the *Proposed tourism strategy* scenario show ecosystem state to be in line with *Baseline*, but with a loss of revenue of ~US$10 million, because of a drastic reduction in the number of arrivals overall (30 thousand compared to ~43 thousand in *Baseline*). However, revenue losses are mitigated by the government's proposed strategy assuming an ecotourist increase in per capita spending of 20%. Note that the model does not account for further conservation actions linked to this strategy, such as improved waste and coastal management, as well as increased support for protected area enforcement, which may very well increase expected benefits (see Section 4).

The final scenario (*Proposed strategy + best practices*) highlights the important impacts of reef fish consumption by resident Palauans and tourists to overall system dynamics (Fig. 6). This scenario seems to be a good compromise between overall arrivals and the promotion of high-value ecotourism (per government proposals), by reducing general tourist visitation rates while taking further actions to maintain a healthy reef state, which in turn ensures continued "attractiveness" for visiting divers (Table 2).

4. Discussion

Our results show that aside from climate change, fishing of reef fish for both tourist and local consumption, has the greatest impacts on Palau's ecosystems. From a tourism and revenue generating perspective, given that ecotourists, on a per capita basis, spend more on-island than regular, increasingly "budget travel", tourists [88–90], management efforts targeted at reducing reef fish consumption and maintaining high ecotourist visitation rates to Palau should be prioritized. Such high ecotourist visitation rates may also maximise employment (not considered explicitly in our model) given the number of services they rely

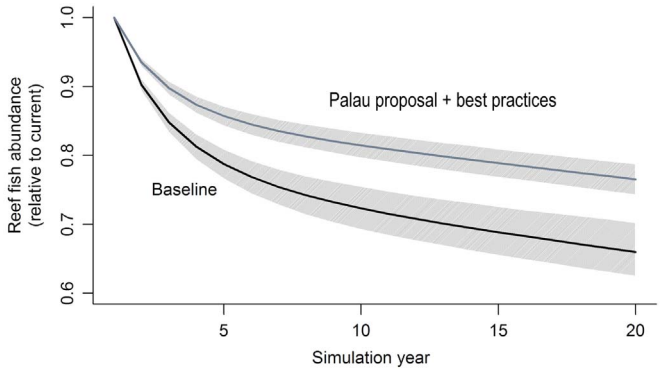

Fig. 6. Reef fish abundance over time (relative to current) given climate change impacts, damaging contacts with the reef by divers, and reef fish consumption by both tourists and resident Palauans (i.e., fishing). "Baseline" represents current conditions with the addition of climate change alone; while "Palau proposal + best practices" represents a scenario in accordance with President Remengesau's tourism strategy targeting fewer visitors overall, a higher proportion of high-paying ecotourists, and a raise in green fees [33], as well as best practices in the form of reduced diver impacts and lower reef fish consumption by both locals and tourists. Note that even in this scenario a decline is registered over time due to the impacts of climate change on reef systems.

upon (e.g., diving, snorkelling, water based activities, tours). High visitation rates, through the levying of green fees, would also generate funds that could be spent on effective management, monitoring and enforcement of local marine reserves. This would in turn act as positive reinforcement for ecotourism development, as healthy reefs, and particularly large fish, are key factors in determining the attractiveness of a site to divers and their willingness to pay higher fees [80,86].

4.1. Climate change impacts

With projected climate change-driven declines in coral cover around the world, the importance of reef fish and shark related attributes as key features for the enjoyment of future divers can only be expected to increase. According to current scenarios [63], increases in sea surface temperatures of between 1 and 3°C by 2100 are projected to significantly impact ecosystems in the tropical Pacific [91-94]. This is reflected in the *Baseline* ecosystem state scenario results (Table 2) and the relatively small differences among the remaining scenarios, particularly for coral. Such impacts are worrisome for local livelihoods, food security [95,96] and the ecotourism industry [97], and may only be somewhat mitigated through sustainable measures in coastal development, targeted interventions as a result of technological improvements and, of course, reductions in greenhouse gas emissions at the global scale. From a tourism perspective alone, this is a challenge that all coral reef diving destinations around the world will face. Thus, potential declines in the perceived attractiveness of Palau's reefs may be mitigated by generalized declines in reef health worldwide [98]. Conservation measures put in place by Palau, including the local Protected Areas Network and the Palau National Marine Sanctuary, are significant steps towards ensuring that ecosystem components, such as large sharks and reef fish, are protected [99] and therefore Palau's world renowned status as a diving destination is maintained. However, to be effective over the long term, such protection measures will need to be met by adequate enforcement, with a recent study showing that remote reefs hosted much lower densities of sharks than those adjacent to the more populated islands due to limited surveillance [100]. The finding that some inner reefs, such as those at Nikko Bay, host isolated communities that live in seawater with a pH that is similar to conditions predicted for 2100 may also help boost local adaptation strategies for Palau's future reefs [101].

4.2. Diving impacts

Reducing diver impacts on reefs by 75% only slightly improved coral reef state over the entire study area (Table 2). However, localized damage caused by divers at popular locations can noticeably reduce reef state and health [31] and thereby considerably decrease the perceived attractiveness of a site, particularly for high-end tourism. Indeed, numerous studies have shown that the extent of site damage is directly related to diving intensity (e.g., [66,67,74]), even for sites, which similar to Palau, tend to largely be "wall dives" or "drift dives". In the face of projected climate-mediated impacts, small improvements may disproportionally benefit reef resilience [102,103], and it seems opportune to stress existing recommendations to ensure ecotourism benefits can be maximised whilst simultaneously reducing environmental impacts (e.g., [65,68,72,77,84,104]). Such actions include:

(i) Reducing diver numbers per site and year to between 5000 [105] and 7000 [66,67]. Assuming that only 50% of tourists dive at some of the most popular locations in Palau, a gross underestimate [30,45], and using 2015 visitation rates as an example, this threshold is currently being exceeded by a factor of 13. Regular monitoring of substrate cover and health at the most popular dive sites could yield site-specific carrying capacity estimates;
(ii) Ensuring that operators participate in, and are encouraged to comply with, responsible dive programmes (e.g., Blue Star and Green Fins) [77], thus reinforcing the environmental education of both dive guides and recreational divers;
(iii) Banning the use of gloves and providing camera users with extra briefings;
(iv) Encouraging entry points for all divers and snorkellers over sandy areas, typically at high tide [31] or in deep water, away from coral, and restricting sensitive reef areas to experienced divers only.

These measures require significant engagement and commitment by all stakeholders [106]. Dive operators in particular should be involved as partners in marine conservation, as a decline in marine resources puts their livelihoods at stake, and their operations can provide an important platform for visitor education.

4.3. Fish consumption impacts

Our findings highlight that, aside from climate change, fish consumption is the main driver of ecosystem state decline in the future. The President's current proposal to develop and foster high-end tourism will reduce the number of tourist arrivals and generate revenues (Table 2) through greater in-country ecotourist expenditure and higher green fees. However, to be ecologically effective, maintain sustainable catch levels, and ensure food security over the long term, the strategy will need to include a reduction in reef fish intake (Fig. 6; Table 2). A recent report on the state of the environment in Palau concludes that although some rules are in place to protect key species (e.g., *maml* and *kemedukl*), regulate the size of reef fish landed, and minimise poaching in MPAs, risks to reef fish from overfishing are currently unmitigated, as few efforts focus on overall catch reduction [11]. Key means to help reef fish populations rebuild include to ensure existing (and future) MPAs are adequately enforced, and to shift consumption pressure to more pelagic species. Recent research based on spatially explicit simulations suggests that the evolution of decreased movement by fish, including tuna and sharks, to evade high fishing pressure can augment the efficacy of marine protected areas [99], highlighting the importance of the former measure. The latter approach would support proposals under the Palau National Marine Sanctuary Act [14], which include: (i) plans to domesticate the local tuna fishery by 2020 and provide local fishermen with mid-range fishing vessels to allow them to access pelagic resources in the domestic fishing zone (DFZ); and (ii) the deployment of Fish Aggregating Devices (FADs) within the DFZ to attract pelagic fish for the benefit of local fishermen

[94,107]. Shifting consumption to more pelagic species will require a deeper understanding of: (i) what the current and likely future demand for tuna is; (ii) what limits and drives current (and future) domestic demand for tuna and reef fish; (iii) what prices different groups of people are willing to pay for different fish; (iv) what the substitutability of tuna/pelagic species for reef fish or other animal proteins is; and (v) what opportunities exist in the value chain to increase returns from marine products whilst reducing overall catches. Some of these questions are currently being addressed by researchers at the Pacific Community, the Nature Conservancy and the Fisheries Forum Agency, among others (P. James, pers. comm.).

Additional measures will also need to be taken to sustainably manage future reef fisheries, including the monitoring of reef fish populations and catches. A recent study engaging fishermen in the collection of data in the Northern Reefs (the two northernmost states of Palau, Ngarchelong and Kayangel) found that 60% of the fish landed are juveniles [10]. Moreover, for some of the most commonly caught species, the authors found that only a very small proportion of the population was breeding. Currently increasing fishing pressure, particularly from night-time spearfishing [48,108], on herbivorous fish [49,50,109] means that these species account for ~40% of total catch [51]. As herbivorous reef fish help control algal overgrowth and facilitate coral recruitment [110], regulations that limit catches of these species in particular would further ensure and promote Palau's reef resilience [111–113], especially in light of climate change projections.

Thus, to effectively promote reef resilience, while maintaining Palauan's traditional lifestyle and boosting revenue from tourism, the currently proposed strategy should include: (i) linking fisheries measures that would allow fish to mature and reproduce before being caught, such as minimum catch/size limits; (ii) the promotion of more conscious targeting behaviours by fishers; and importantly (iii) focused efforts at actively promoting the targeting and consumption of tuna and other pelagic species instead of reef fish. These measures, together with a rigorous catch monitoring program would significantly strengthen and complement existing efforts by the government.

4.4. Sustainable coastal management

The model presented here includes tourist impacts on marine ecosystem health from a fish consumption and damaging diver behaviour perspective, and partially accounts for losses that accrue from increased sedimentation, sewage discharge, solid waste overload, unsustainable use of energy, or any other impacts related to developments onshore [114]. Palau's hotel industry currently mainly accommodates low-budget travellers. Ensuring that a shift to high-end tourists is successful, as mandated by the President's strategy [34], will likely require new developments that adequately suit the needs and tastes of this market. These developments are often associated with large-scale clearing, soil erosion and increased terrestrial runoff. The recent State of the Environment Report includes the number of earthmoving permits showing a worrisome trend [11]. Land-based sediments have been linked to severe reef degradation due to declines in coral cover, lower recruitment and excessive growth of algae [115–117]. It is therefore important that any new developments require a more rigorous environmental impact assessment study. Critically, coastal management efforts aimed at addressing pollution as well as sedimentation and nutrient loading concerns [118,119] would need to ensure that buffer zones along coastlines (e.g., coastal vegetation including mangroves and seagrass beds [116]) are maintained, and governance and legislation strengthened to ensure the sustainable use and protection of coastal habitats. The government together with developers have significant roles to play in building political consensus for land-use planning, as well as adopting and implementing environmentally and socially-sound policies and practices [11,33,88,120] to avoid the degradation of Palau's natural heritage. Such effective local management measures, which benefit from the engagement and support of local communities, could lead to a slower decline in ecosystem health due to climate change impacts alone, and lend the ecosystem greater resilience and maximise its adaptive capacity to future changes [102].

5. Conclusions

This study provides (i) a framework to assess the impacts of different sectors on reefs' social-ecological long-term health and, (ii) based on scenarios, tangible inputs for the development of suitable guidelines and management strategies to safeguard the long term sustainable use of marine resources, to better inform the sustainable growth of tourism, to maximise revenue generation, and to ensure local food security. Such a scenario-oriented approach also provides a meaningful starting point to stimulate further discussions [121,122] about the future, and what measures may be necessary to stay proactive rather than reactive in response to challenges. Findings highlight that a decline in reef fish consumption and a shift to more pelagic species are required to achieve the above goals.

The aim of this study was not to provide an exact estimate of decline in marine resources' state caused by tourism and other activities, but rather to assess their impacts relative to each other and provide relevant insights for policy. While a wide number of studies have been published on the impacts of divers on reef state (e.g., [65,123,124]), as far as the authors are aware, no study to date has sought to quantify the impact of tourists and locals on marine resources through fish consumption and integrate these with other challenges, such as climate change. The model presented here focuses on coastal resources in Palau and only conceptually includes the pelagic realm. With the relevant and appropriate data it could readily be expanded to encompass those dynamics and be easily adapted to other island situations or local cases in non-SIDS.

To be effective and long-lasting, strategies implemented by the government of Palau will need to (i) emerge from consultations with relevant local stakeholders; (ii) ensure that revenues accrue to the local economy; and (iii) be complemented by targeted ecological awareness-raising campaigns with both locals and visitors to identify their impacts and measures needed to redress them. All activities should be placed under an adaptive management framework to regularly review and improve the codes of conduct utilised.

Acknowledgments

This work was supported by the Nippon Foundation Nereus Program, a collaborative initiative between the Nippon Foundation and partners including the University of British Columbia and ANCORS, University of Wollongong. The funder had no part in or influence on study design, analysis and interpretation of data, in the writing of the manuscript or in the decision to submit the article for publication. We're grateful to L. Lafreniere for Figs. 1 and 4. We also thank Y. Ueda from The Nature Conservancy; I. Bertram and P. James from the Pacific Community; W. Swartz from the Ocean Policy Research Institute, the Sasakawa Peace Foundation; and P. Mumby from University of Queensland for useful insights and helpful suggestions; as well as the constructive comments from two anonymous reviewers.

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